Version HJJ/2

EGT3
ENGINEERING TRIPOS PART IIB

Wednesday 6 May 2026   14.00 to 15.40

Module 4B19

RENEWABLE ELECTRONIC POWER

*Answer not more than **three** questions.*

All questions carry the same number of marks.

*The **approximate** percentage of marks allocated to each part of a question is indicated in the right margin.*

*Write your candidate number **not** your name on the cover sheet.*

STATIONERY REQUIREMENTS
Single-sided script paper

SPECIAL REQUIREMENTS TO BE SUPPLIED FOR THIS EXAM
CUED approved calculator allowed
Engineering Data Book
Attachment: Sheet of Formulae and Constants (1 page)

10 minutes reading time is allowed for this paper at the start of the exam.

You may not start to read the questions printed on the subsequent pages of this question paper until instructed to do so.

You may not remove any stationery from the Examination Room.

1 (a) Your task is to evaluate wind turbines for a new site.

(i) How is the extractable wind power related to the wind speed? [10%]

(ii) Sketch a typical wind turbine-generator power versus wind speed characteristic. Assume a power rating of 10 MW for the generator and a wind speed rating of 10 $\mathrm{m\,s^{-1}}$. [10%]

(iii) Define the terms ‘cut-in’, ‘rated’, and ‘stall’ with respect to wind speed and label them on the sketch. [10%]

(iv) Describe two ways in which the wind turbine power can be controlled so that the rated power is not exceeded between rated and stall wind speeds. [10%]

(b) A wind turbine site offers wind speeds of 2 $\mathrm{m\,s^{-1}}$ during 11% of the time, 6 $\mathrm{m\,s^{-1}}$ during 41%, 10 $\mathrm{m\,s^{-1}}$ during 22%, 14 $\mathrm{m\,s^{-1}}$ during 14%, 18 $\mathrm{m\,s^{-1}}$ during 8%, and 22 $\mathrm{m\,s^{-1}}$ during 4%. The wind turbine has a rated output power of 10 MW and a rated wind speed of 12 $\mathrm{m\,s^{-1}}$. The cut-in speed is 3 $\mathrm{m\,s^{-1}}$ and the stall speed 20 $\mathrm{m\,s^{-1}}$. The turbine is to be operated at its optimum tip-speed ratio between the cut-in and rated speeds.

(i) Determine the electrical output power for each given wind speed and calculate the total annual energy. You may ignore the conversion losses. [30%]

(ii) What is the capacity factor of this wind turbine installation? [10%]

(c) A more power-dense generator technology can offer a rated power of 13 MW in the otherwise same turbine.

(i) Evaluate the total annual energy and the capacity factor for this new generator technology with the same cut-in and stall speeds as in (b). Assume that the rest of the turbine can manage the higher power. [10%]

(ii) Provide at least one option through which the power density could be improved. [10%]

2 (a) Name at least three different levels that the British electrical grid uses and describe which function each of them serves. To which of them is most photovoltaic power connected, and to which wind power? Explain the reasons. [10%]

(b) Give at least two problems of an increasing share of wind and solar power in the electric grid on the system level. [10%]

(c) Give at least three problems of an increasing share of wind and solar energy in the electric grid on the local level, where most residential buildings are connected. [20%]

(d) Explain the reasons for the grid problems from parts (b) and (c) and discuss solutions to reduce those problems. [20%]

(e) The United Kingdom and neighbouring countries will build various electrical interconnections to the larger European grid. Give at least two reasons why such interconnections would be advantageous for larger shares of renewable power and explain in detail. Which technology will be used for these interconnections? Give at least two reasons why this technology is appropriate for these interconnections. [30%]

(f) What makes offshore wind an attractive energy source? Which options are there to transport offshore wind energy to the electric grid on land? Which option is used when and why? [10%]

(TURN OVER

3 (a) Explain the operational parameters of short-circuit current, open-circuit voltage and fill factor, and how these parameters are related to solar cell efficiency. [10%]

(b) Describe one type of solar concentrator technology used with photovoltaic cells and sketch a ray diagram indicating how it focusses sunlight. Comment on its advantages and disadvantages. [20%]

(c) Explain how short-circuit current and open-circuit voltage change if illumination conditions are changed from 1-sun to 10-sun concentration. Give your reasoning. [20%]

(d) Explain how the fill factor changes if illumination conditions are changed from 1-sun to 1000-sun concentration. Give your reasoning. [10%]

(e) Explain how the output stage of a solar inverter converts DC power to frequency- and phase-controlled AC power through the use of pulse-width modulation. [40%]

4 A solar panel manufacturer is making a p–n junction solar cell from monocrystalline Si with the following parameters at an operating temperature of 300 K:

Base wafer dopant density (p-type)	10^{17} cm^{-3}
n-region dopant density	10^{19} cm^{-3}
Intrinsic carrier density	5×10^{10} cm^{-3}
Hole minority carrier diffusion length	100 nm
Electron minority carrier diffusion length	100 μm
Hole minority carrier lifetime	1 ns
Electron minority carrier lifetime	1 μs
Junction area	100 cm^2

The junction is formed such that the n-region penetrates to a depth of 2 μm from the surface, above a p-type region extending a further 250 μm to form the bulk of the cell.

(a) Calculate the built-in potential of the junction. [10%]

(b) Starting from Poisson's equation,

$$\frac{\partial^2 V}{\partial x^2} = \frac{\rho}{\epsilon_0 \epsilon_r},$$

where ρ is the charge density, calculate the width of the depletion region on the p-type side and the peak electric field within the junction under equilibrium conditions. [30%]

(c) Calculate the reverse saturation current of the junction. [10%]

(d) Under a forward bias of 0.55 V, calculate the current through the solar cell

(i) under dark conditions; [10%]

(ii) under illumination with an optical generation rate of 10^{17} cm^{-3}s^{-1}. [10%]

(e) Describe how the performance of the solar cell might change if the junction depth was decreased to 100 nm. [20%]

(f) Describe a step in the manufacturing of Si solar panels that is performed to increase shunt resistance. [10%]

END OF PAPER

THIS PAGE IS BLANK

4B19 RENEWABLE ELECTRONIC POWER **Formulae and Constants**

Built-in potential for a solar cell

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_D N_A}{n_i^2}\right)$$

Reverse saturation current of a p-n junction diode

$$I_s = eA\left[\frac{n_i^2 D_e}{N_A L_e} + \frac{n_i^2 D_h}{N_D L_h}\right]$$

where

$$L_{e,h} = \sqrt{D_{e,h}\tau_{e,h}}$$

Optical generation rate in a semiconductor at distance x from the light-entering surface

$$g_0(x) = \int_{\lambda_1}^{\lambda_2} \phi_0(\lambda)\alpha(\lambda)\exp(-\alpha(\lambda)x)\,d\lambda$$

where $\phi_0(\lambda) = (1 - R(\lambda))\phi(\lambda)$ and $\phi(\lambda)$ is the incident photon flux at wavelength λ of the solar spectrum.

Reflection co-efficient at normal incidence from the third layer of a 3-layer system comprising of a thin film sandwiched between two bulk materials extending away fromtheir interfaces with the thin film is given as:

$$R = \frac{n_2^2(n_1 - n_3)^2\cos^2\vartheta + (n_1 n_3 - n_2^2)^2\sin^2\vartheta}{n_2^2(n_1 + n_3)^2\cos^2\vartheta + (n_1 n_3 + n_2^2)^2\sin^2\vartheta}$$

where

$$\vartheta = \frac{2\pi n_2 d}{\lambda}$$

and n_1, n_2 and n_3 are the refractive indices of 3 materials m_1, m_2 and m_3 respectively: d is the thickness of the thin film m_2 sandwiched between materials m_1 and m_3. Direction of light flow is taken to be from m_1 to m_3.

Fill Factor for a Si solar cell

$$FF_0 = \frac{\frac{eV_{oc}}{kT} - \ln\left(\frac{eV_{oc}}{kT} + 0.72\right)}{\frac{eV_{oc}}{kT} + 1}$$

where V_{oc} is the open-circuit voltage for the cell.

Constants

Electronic charge unit **e**: 1.602×10^{-19} C
Boltzmann's constant **k**: 1.381×10^{-23} J K^{-1}
Speed of light **c**: 2.998×10^{8} m s^{-1}
Planck's constant **h**: 6.626×10^{-34} J s
Dielectric permittivity free space $\boldsymbol{\varepsilon_0}$: 8.854×10^{-12} F m^{-1}
Relative permittivity of Si $\boldsymbol{\varepsilon_r}$:11.9
Refractive index (for weakly and non-absorbing wavelengths) $\boldsymbol{n} = \sqrt{\varepsilon_r}$
Band-gap energy of Si: $\boldsymbol{E_g}$:1.12 eV